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Micromachined flow sensors—a review

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Micromachining technology has been developed very rapidly in recent years. This technology takes advantage of the benefits of semiconductor technology to address the manufacturing and performance requirements of the sensors industry. The compatibility of micromachining and microelectronics makes the integration of electronics and mechanical elements possible. This covers the need of low-cost, accurate and reliable sensors for industrial and consumer product applications. An important product of micromachining technology is the micro-mass flow sensor which has a history of over 20 yrs. This paper presents a review of the research and development of micromachined flow sensors which have been done in the last few years by international academic and industrial institutions. © 1997 Elsevier Science Ltd.

Keywords: micromachining; semiconductor sensor; thermal flow sensor; mechanical flow sensor; micro electromechanical systems

1. Introduction

In the past 20 yrs, the application of microelectronic technology to the fabrication of mechanical, thermal and optical devices has greatly stimulated research and development of micromachined sensors, generally, and more specifically the silicon sensor. Because sensors for different physical variables are structurally different, there is no single technology that allows the fabrication of a wide variety of sensors and integrated electronics. Currently, there are four major classifications of micromachining technology: bulk-micromachining, surface-micromachining, epi-micromachining (or surface-proximity-micromachining) and LIGA-micromachining (LIGA: german acronyms for **Li**thographie-**G**alvanoformung-**A**bformung) [1–3]. The last one is because of its incompatibility with microelectronics not often used for the fabrication of micro sensors.

In bulk-micromachining, the sensors are shaped by etching a large single-crystal substrate. A high-resolution etch and tight dimensional control are provided using anisotropic etching techniques. Surface-micromachined sensors are constructed entirely from thin films. Free standing and movable parts can be fabricated using sacrificial etching. Single-crystal materials used in bulk-micromachining have well-defined properties in contrast to those of amorphous polycrystalline thin films, hence yielding sensors with reproducible characteristics. The bulk-micromachining has the disadvantage that the devices are generally relatively large and therefore consume most of the chip area. A recent development which has tried to ta e the advantages from both technologies while min- sing the disadvantages, is epi-micromachining. Epi-micromachining is essentially front-side bulk micromachining, using wet or dry etching, where the epitaxial layer forms the mechanical structure.

The flow measurement is a classical field of measurement technology. The working principles contain nearly all domains of physics (Figure 1) [4]. The fast development of micromachining technology makes the realisation of conventional measurement principles possible. This opens a new market for new applications and products.

In the year 2000, flow measurement and control with micromachined flow sensors will share about 19% of the MEMS-market (MEMS: **m**icro **e**lectro**m**echanical **s**ystems) which will amount in all probability to US$ 14 billion [5]. The growing market of micromachined flow sensors requires a lot of research and development of this new technology and its use for fabrication of flow sensors. Governed by their small geometry, the biggest advantages of micromachined flow sensors are the low energy consumption and the possibility to measure very small mass flow (micro litres per minute).

The first flow sensor based on silicon technology was presented in 1974 by van Putten and Middelhoek [6]. In the 1980s when the micromachining and micro-electromechanical systems were established as common expressions in the professional world, some industrial firms developed the new product 'micromachined flow sensor' based on the hot-film principle. In this type of flow sensor, the fluid streams around the sensor.

From the end of the eighties to the beginning of the nineties, the development of micromachined sensors has been an important research field of numerous international academic institutions. In the 1990s, the development tends towards the fabrication of complex micro fluidic systems (micro flow sensors, pumps and

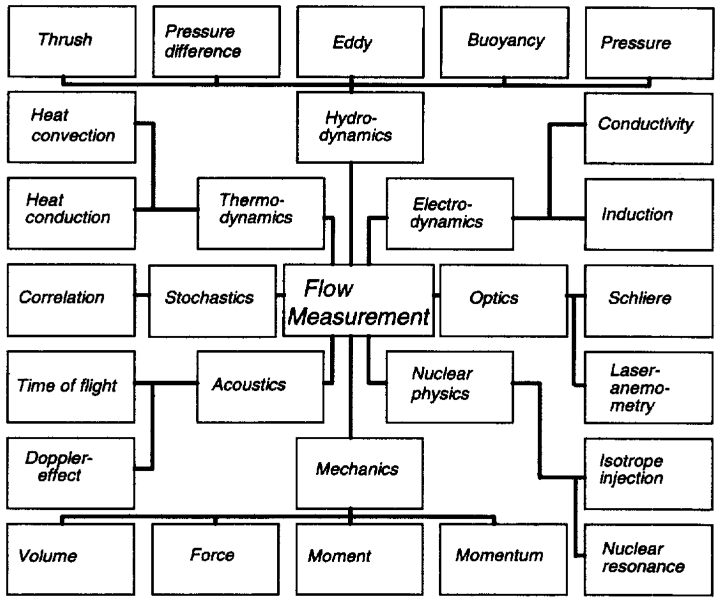

Figure 1 Physical principle of flow measurement [4]

valves in a system). Therefore, there is a need for a flow sensor that can measure very small flow rates. The result of this challenge is a new class of micromachined flow sensors which have an integrated micro channel. In this type of micromachined flow sensor, the fluid streams inside the sensor. The first sensor of this type was presented by Petersen in 1985 [7].

Because of the high dynamics resulting from the miniaturisation, there are new interesting applications for micromachined flow sensors. An example is the thermal microphone of the MESA-institute (University Twente, Netherlands) that is able to measure acoustic flow [8].

Because of the enormous number of already developed micromachined flow sensors which are based on the thermal principle, there are two classifications: non-thermal and thermal flow sensors.

2. Non-thermal flow sensors

All the already realised non-thermal flow sensors are based on the mechanical working principle. For example, the flow can be measured indirectly by the drag force using a silicon cantilever. In laminar flow conditions, with a small Reynolds number, the drag force parallel to the flow direction is given by the Navier–Stokes-law:

$$F = CLv\eta, \tag{1}$$

where F is the drag force, C a constant depending on the form of the cantilever, L the dimension of the cantilever, v the flow velocity and η the dynamic viscosity of the fluid. The evaluation of the force, as well as the flow velocity, results in using integrated piezoresistive resistors on the cantilever [9–11] (Figure 2).

In refs [12, 13], the working principles are based on the pressure measurement using capacitive and, respectively, piezoresistive pressure sensors. This method uses the linear dependence of pressure drop on the laminar flow velocity [14]:

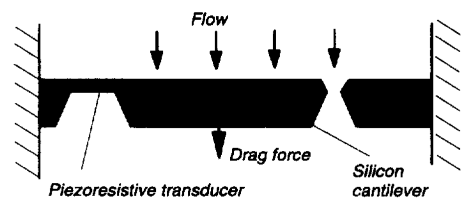

Figure 2 The cantilever is located in the flow. The distortion of the cantilever is evaluated by using integrated piezoresistive silicon resistors

$$\Delta P = \frac{C}{2} \frac{L}{D_h^2} v\eta, \tag{2}$$

where ΔP is the pressure drop, C is the friction coefficient (C = 64 for circular cross-section), L is the channel length, D_h is the hydraulic diameter ($4A/U$, A: cross section, U: wetted perimeter), v is the flow velocity and η is the dynamic viscosity of the fluid (Figure 3).

An array of piezoresistive pressure sensors for measuring very small gaseous flow in microchannels was developed at the University of California, Los Angeles. The structure was fabricated by using surface-micromachining [15].

A true mass flow sensor is achieved by using the Coriolis-principle (Figure 4). The general expression describing the Coriolis-force which acts on an oscillating tube with fluid flowing inside can be written as:

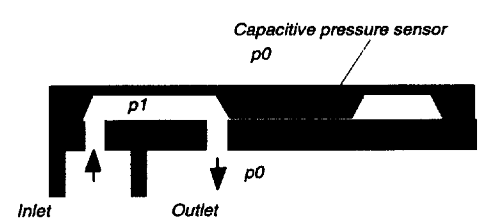

Figure 3 The pressure difference caused by the flow can be measured by using an integrated pressure sensor

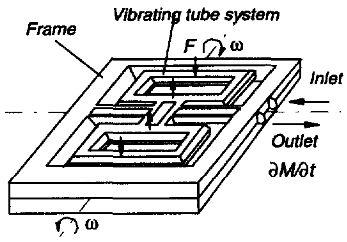

Figure 4 The Coriolis mass flow resonator consists of two serially connected tube loops located symmetrically in one plane. The tube structure is excited using an external electrode. The angular amplitudes of the excitation vibration and the Coriolis-twisting is detected using a two-dimensional lateral photodetector and a lock-in amplifier [16]

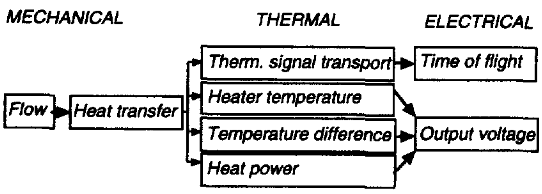

Figure 5 The three signal domains and signal transport of a thermal flow sensor

$$\mathbf{F} = 2\frac{\partial \mathbf{M}}{\partial t} \times \omega, \qquad (3)$$

where $\mathbf{F}$ is the force per unit tube length, $\mathbf{F} = \partial\mathbf{M}/\partial t$ is the mass flow velocity in the tube and ω is the angular velocity of the oscillating tube. Flow sensors with the Coriolis-principle using bulk-micromachining were presented for the first time by the Swedish Royal Institute [16]. This sensor can be used for measuring the fluid density [17].

The disadvantage of mechanical flow sensors lies in the dependence of the force, pressure difference and Coriolis-force on the fluid density. The density of most fluids depends on the temperature. Therefore, a temperature compensation is a compelling necessity.

A volume counter as well as a micro turbine can be realised using the LIGA-micromachining. The detection of the rotation can be obtained by using integrated optics. A bistable fluidic element is presented in Ref. [18].

3. Thermal flow sensors

International research works on the field of micromachined flow sensors showed that because of their structural and electronic simplicity thermal sensors can be realised diversely and easily using the micromachining technology. Figure 5 shows the general signal transport of a thermal flow sensor.

With two heater control modes and two evaluation modes, there are six operational modes shown in Table 1 and three types of thermal flow sensors:

- Thermal mass flow sensors which measure the effect of the flowing fluid on a hot body (increase of heating power with constant heater temperature, decrease of heater temperature with constant heating power). They are usually called hot-wire and hot-film sensors.
- Thermal mass flow sensors which measure the asymmetry of temperature profile around the heater which is modulated by the fluid flow. They used to be called calorimetric sensors.
- Thermal mass flow sensors which measure the pass-

Table 1 Operational modes of thermal mass flow sensors

Heater controls	Constant heating power		Constant heater temperature	
Evaluation	Heater temperature	Temperature difference	Heating power	Temperature difference
Operational modes	Hot-wire and hot-film type Time-of-flight type	Calorimetric type	Hot-wire and hot-film type Time-of-flight type	Calorimetric type

Table 2 Transducing principles and realisation of thermal transducers using micromachining technology

Principle	Realization examples	Application
Thermoresistive	• Platinum • Polysilicon • Silicon • Metal alloys (NiCr, NiFe)	• Temperature measurement • Temperature difference measurement • Heating power measurement
Thermoelectrical	• pSi–Al (bipolar-technology) • PolySi–Al (CMOS-technology) • pPolySi–nPolySi	• Temperature measurement • Temperature difference measurement
Thermoelectronical	• Transistors • Diodes	• Temperature measurement • Temperature difference measurement
Pyroelectrical	• $LiTaO_3$ as pyroelectrical material with metal- or silicon resistors as Heater and electrodes	• Heating power measurement
Frequency analog	• SAW-oscillator, Lamb-wave-oscillator as temperature sensors	• Temperature measurement

age of time of a heat pulse over a known distance. They are usually called time-of-flight sensors.

The measurement of the heating power on a constant heater temperature, well known as the hot-wire and hot-film principle, respectively, and the evaluation of the asymmetry of the temperature distribution are the most commonly used working principles. The detection of the time-of-flight of a heating pulse using the correlation principle is very interesting. This principle is unfortunately rarely mentioned in the published papers.

Following, micromachined thermal flow sensors are classified after their transformation principles of the thermal signal (heating power or temperature) into the electrical signal (current or voltage). Table 2 shows an overall view of this principle. The indirect transformation over an oscillating mechanical element is called, in this paper, the frequency analog principle. The principle of the thermal sigma-delta-converter [53] actually has a frequency output, but does not belong to this kind of working principle.

3.1. Thermoresistive flow sensors

The first thermal flow sensor based on silicon technology was published by van Putten and Middelhoek of the University of Technology, Delft in 1974 [6]. Beginning with the hot-film principle, the sensor was developed to an integrated silicon double bridge anemometer [19].

Furthermore, the Toyota Central Research and Development Laboratories developed another thermoresistive silicon flow sensor in 1986 [20]. The working principle is based on the conventional hot-film anemometry (Figure 6). The sensor chip has two platinum thin-film resistors which are used as a heating element and a fluid temperature sensing element. The resistors are located in the centre of the oxidised porous silicon diaphragm and the rim of the chip, respectively.

A year later, the same principle was presented by Central Research Laboratories of Scharp Corporation [21]. Glass was used as the carrying substrate. For the control of a constant heater temperature, a heater temperature sensing resistor was integrated.

The flow sensor of Honeywell Physical Sciences Center (USA) [22] consists of temperature sensitive resistors (Permalloy) laminated within a 1 μm thin thermal isolated silicon nitride layer, which are suspended in the form of two bridges over an etched pit in the silicon (Figure 7). The commercial type of this sensor has platinum resistors. The chip is located in a flow channel. The heater is kept on a constant

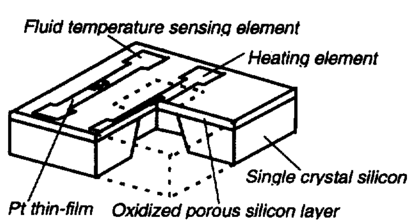

Figure 6 Structure of the sensor chip of Toyota Central Research and Development Laboratories [20]

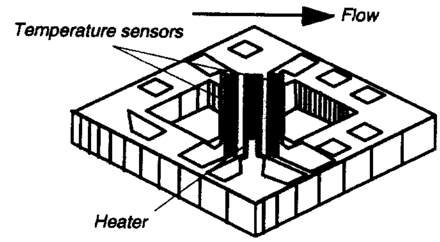

Figure 7 The heater and temperature sensors are located on a silicon nitride bridge. The asymmetry of the temperature distribution is evaluated [22]

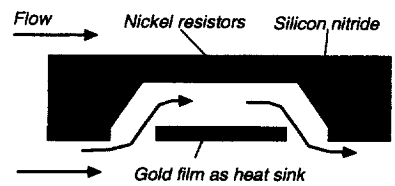

Figure 8 The heat sink and flow guide on the back side allow the temperature distribution on the diaphragm to be modulated. Two resistors on the rim measure the ambient temperature [23]

temperature and creates by zero-flow a symmetrical temperature distribution around itself. The upstream and downstream temperature sensing resistors measure the asymmetry of the temperature distribution caused by the flow. The resistance difference can be evaluated using a Wheastone bridge and a differential instrumentation amplifier.

The development of the Technical University of Berlin [23] is similar to the sensor in Ref. [22]. A heat sink and flow guide integrated on the back side of the flow sensor is used to achieve an extended measurement range (Figure 8).

The flow sensor developed by the Berkeley Sensor and Actuator Center (USA) has improved thermal isolation resistors which are highly doped polysilicon bridges [24] (Figure 9).

At the international conference *Transducers* '85, a micromachined flow sensor with integrated micro channel was presented for the first time by Peterson of Transensory Devices Inc. (Fremont, USA) [7]. The micro channel was fabricated using the bulk-micromachining technology. The sensor consists of a metal thin-film resistor suspended in the channel and another resistor on the rim (Figure 10).

The flow sensor presented by the University of Twente (Netherlands) has suspended CrAu-resistors as the heater and temperature sensors (Figure 11), [25]. The resistors are carried by a silicon nitride grid. The flow channel is fabricated by using silicon etching and anodic bonding.

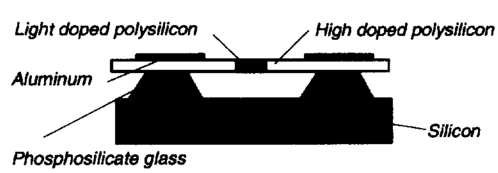

Figure 9 The hot-wire principle can be realised using the surface-micromachining [24]

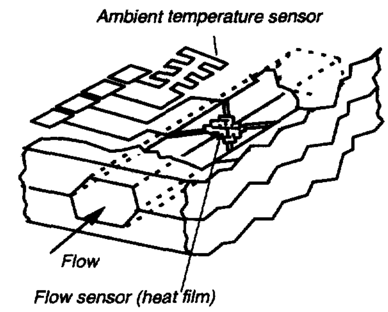

Figure 10 The heat-film resistor is suspended in a micro channel [7]

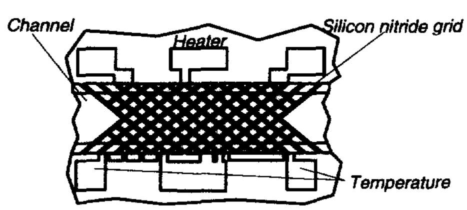

Figure 11 The heater and temperature sensors are carried by a silicon nitride grid which is suspended in the integrated flow channel [25]

A further flow sensor with integrated flow channels was fabricated by the Technical University of Chemnitz-Zwickau [26]. The sensor has for the first time a resistor structure outside the flow channel. The direct contact to fluid can be avoided. The further development of this sensor has resistor structures on a thin silicon diaphragm which improves the sensor dynamics (Figure 12), [27].

The flow sensor published in Ref. [28] is based on the principle of the hot-film anemometry. The sensor consists of an array of resistors which are used for the control and measurement of the heat power at a constant heater temperature. The similar principle was presented in Ref. [29]. The polysilicon resistor is located on a silicon oxide/silicon nitride double layered isolator film.

3.2. Thermoelectric flow sensors

At the Delft University of Technology (Netherlands), a flow sensor for measuring flow rate and flow direction was developed [30–34]. In these sensors, thermopiles (silicon–aluminium coupling) in a two-dimensional

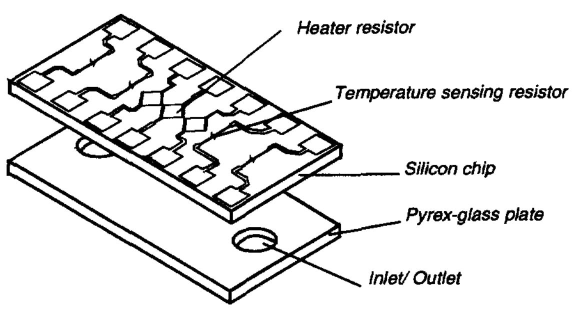

Figure 12 The heater and temperature sensors are carried by a silicon diaphragm which covers the integrated flow channel [27]

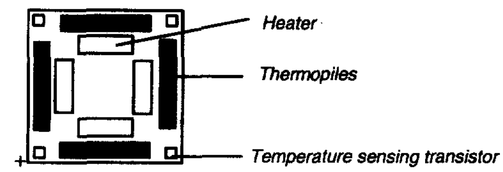

Figure 13 The arrangement of four thermopiles allows a two-dimensional flow measurement

arrangement are in use (Figure 13). The heater resistor is located on a suspended thin silicon plate for improvement of the heat isolation. In operation, the sensor lies directly in the fluid flow. A similar solution has been shown by the Technical University of Darmstadt [35].

In the flow sensor developed by the Physical Electronics Laboratory Zürich (Swiss), a polysilicon heater and n/p-silicon thermopiles as temperature sensors are in use. The sensor was fabricated by using the standard CMOS-technology [36]. Further developments of this sensor with thermopiles made from aluminium/polysilicon were published in Refs [37–39]. The influence over sensor characteristics of geometrical parameters like the distance between heater and temperature sensors, length of the thermopiles and the height of the flow channel was investigated in refs [37, 39]. The two-dimensional version of this sensor was published in Ref. [38].

3.3. Thermoelectronic flow sensors

At the development of Toshiba Research and Development Centres, the heat source and temperature sensors are bipolar transistors [40]. The heat power and asymmetry of the temperature profile are simultaneously evaluated. Therefore, the heat power signal and temperature difference upstream and downstream can be used for detection of flow velocity and flow direction, respectively.

In contrast to other works, the flow sensor of the Nanjing Institute of Technology (China) has an integrated amplifier in the sensor chip. Heater and temperature sensors are field effect transistors [41] (Figure 14).

A similar solution using CMOS standard technology was published by the Chalmers University of Technology (Sweden) [42]. In contrast to the conventional hot-film principle, the heater is controlled by using the pulse-modulation of the heating current. The ratio between high and low output times of the current signal is a sensitive measure of gas flow velocity (Figure 15).

Diodes are heater and temperature sensing elements in the flow sensor fabricated by using CMOS-

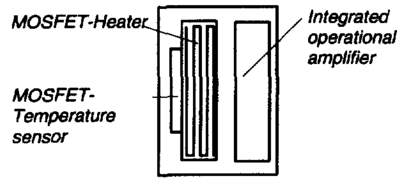

Figure 14 The hot-film principle was realised by using FETs [41]

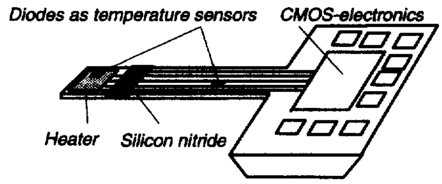

Figure 15 For improvement of the thermal behaviour, the sensor element is located on a silicon cantilever [42]

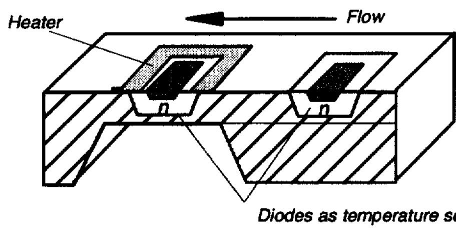

Figure 16 The heater is thermally isolated by buried silicon oxide [43]

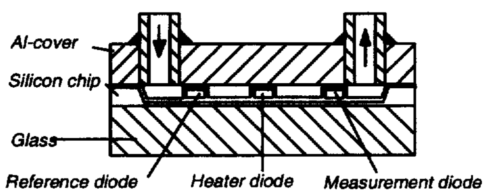

Figure 17 Diodes used for heating and temperature sensing are located in a flow channel [45]

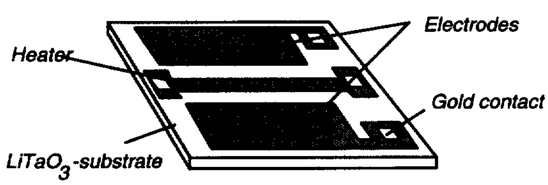

Figure 18 The pyroelectric substrate is heated periodically. The cooling of the sensor can be detected by the pyroelectric current [46]

technology of the Fraunhofer Institute for Microelectronic Circuits and Systems (Duisburg, Germany) [43]. The thermal isolation was carried out by using buried silicon oxide around the heater (Figure 16).

The Institute of Micro-Technology (University Neuchâtel, Swiss) published a similar solution [44]. The hot-film principle was used and the heating power was controlled by using diodes for the heater temperature measurement.

The flow sensor of the Technical University Denmark was fabricated using standard silicon bulk-micromachining. Heating and sensing elements are diodes which are positioned beneath diamond-shaped silicon pyramids. The pyramids are placed in the flow channel in order to obtain good thermal contact between fluid flow and heating as well as sensing elements [45]. With this sensor, the time-of-flight principle was in use for the first time (Figure 17).

3.4. Pyroelectric flow sensors

The flow sensor of the University of Pennsylvania (USA) used a pyroelectric element [46] (Figure 18).

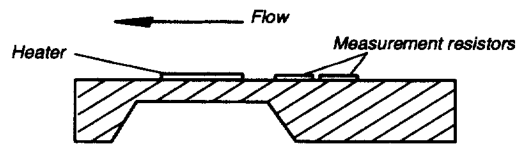

Figure 19 The diaphragm is thermally excited. The oscillation is detected piezoresistively [49]

The working principle is based on the dependence of surface charge of a pyroelectric material on the change of the supplied heat. The pyroelectric current is given by [47]:

$$I = p.A.\frac{dT}{dt}, \tag{4}$$

where p, A, T are the pyroelectric constant, the area of the detecting electrode and temperature of the pyroelectric material, respectively. Therefore, a sinusoidal electric current is supplied to the heater at a frequency f, which both heats the pyroelectric substrate to a stationary d.c. temperature and produces an a.c. sinusoidal temperature variation at a frequency $2f$. The heat from the thin-film heater flows through the substrate and is dissipated to the flow. The a.c. temperature variation under the two electrodes includes pyroelectric currents in each of the symmetrically disposed measuring electrodes. The a.c. pyroelectric currents generated at the two symmetric electrodes produce the sensor signal. Because Lithiumtantalat $LiTaO_3$ has a fairly high pyroelectric coefficient $p = 2.3{\cdot}10^{-4}$ [$A\,s\,m^{-2}{\cdot}K^{-1}$] which is not affected by ambient temperatures up to about 200°C [47], this pyroelectric material was chosen. The electrodes and heater may be made from NiCr or gold thin film [48].

3.5. Frequency analog sensors

Frequency analog sensors can be realised by using thermal excitation and evaluation of oscillating frequency [49, 50] (Figure 19). The operational principle is based on the temperature dependence of oscillating behaviour of mechanical function elements (cantilever, diaphragm). A change of temperature causes a change of mechanical stress in the elements, which leads to a change of the resonant frequency.

The flow sensor of the Department of Electrical and Computer Engineering Marquette University (USA) is based on the dependence of surface wave frequency on the temperature. The heater is fabricated using a meander-shaped thin-film resistor [51] (Figure 20). The Delft University of Technology gives a similar solution using Lamb-wave [52].

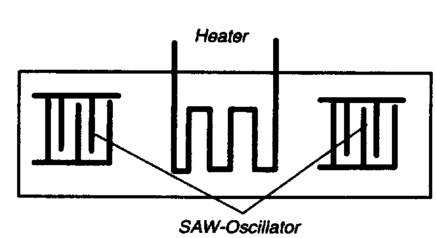

Figure 20 The heater is located between two SAW-oscillators. The cooling of the sensor chip can be detected

Table 3 Performance of micromachined flow sensors for gas flow velocity measurement

Type	Transducing principle	• Chip size (L × W × H) • Sensor size (L × W × H)	•Measurement range • Zero-flow dissipation • Over-temperature of heater	Response time	Ref.
Hot-wire and hot-film	Thermoresistive (hot-film)	• 4 mm × 4 mm × 360 μm • < 1 mm × 1 mm	• 0–14 m/s air flow • 0.2 mW/K • 10 K	10 msec	[20]
	Thermoresistive (hot-film)	• 10 mm × 1.6 mm • < 1.6 mm × 1.6 mm	• 0–2.3 m/s air flow •0.372 mW/K • 5–25 K	1 sec	[21]
	Thermoresistive (hot-wire)	• no data • 200 μm × 5 μm × 1.5 μm	• 0–2 m/s air flow • 1.12 × 10^{-2} mW/K • 100 K	3 sec	[24]
	Thermoelectronic (hot-film)	• 2 mm × 1.4 mm × 380 μm • 0.3 mm × 0.4 mm × 30 μm	• 2–30 m/s air flow • 1.12 × 10^{-2} mW/K • 146 K	no data	[42]
	Thermoelectronic (hot-film)	• 1 mm × 5 mm • 260 μm × 260 μm × 5 μm	• 0–8 m/s air flow • 2 mW/K • 13 K	20 μsec	[43]
	Pyroelectric (hot-film)	• 3.8 mm × 7.8 mm × 0.2 mm • 3.8 mm × 3.8 mm × 0.2 mm	• 0–15 m/s helium flow • no data	no data	[46]
Calorimetric	Thermoresistive	• no data • 400 μm × 500 μm	• 0–1.3 m/s air flow • 6.7 × 10^{-2} mW/K • 100–160 K	10 msec	[22]
	Thermoresistive	• 4 mm × 6 mm • 1.5 mm × 2 mm	• 0–2 m/s air flow • 0.14 mW/K • 55 K	< 150 msec	[23]
	Thermoelectric	• 4 mm × 3 mm • 1.5 mm × 2 mm	• 0–25 m/s air flow • 15 mW/K • 24 K	5 sec	[30]
	Thermoelectric	• 2 mm × 1.28 mm • no data	• 0–20 m/s air flow • 0.38 mW/K • no data	No data	[35]
	Thermoelectric	• 500 μm × 500 μm • 160 μm (length of thermopile)	• 0–25 m/s air flow • 0.05 mW/K • 200 K	4 ms	[36]
	Thermoelectronic	• 1 mm × 1.9 mm • no data	• 0–0.5 m/s air flow • no data • 25 K	40 s	[41]
Time-of-flight	Thermoresistive	• no data • 1.5 mm × 2 mm	• 0–0.1 m/s helium flow • no data • no data	No data [56]	

4. Applications of micromachined flow sensors

Micromachined flow sensors described in the last two sections cover a wide range of medium, flow range and applications from macroscopic air velocity measurements to the measurement, as well as control, of microlitres-per-minute of liquid flow.

Thermal flow sensors are suitable for the measurement of gas flow velocity. The sensor chip is located directly in the gas flow. Table 3 shows a survey of the performance of the above described sensors. With the typical square-root characteristic (Figure 21), the large measurement range of the hot-wire and hot-film is recognisable in Table 3. The calorimetric type shows a high sensitivity and good resolution in the small flow range. Figure 22 illustrates the typical sensor characteristic of calorimetric type in the operational mode of constant heating power. The linear part of the sensor characteristic is used for the evaluation in refs [22, 23, 41]. Because of the constant heating power, the temperature difference reaches a maximum and decreases with the increasing part. Therefore, the

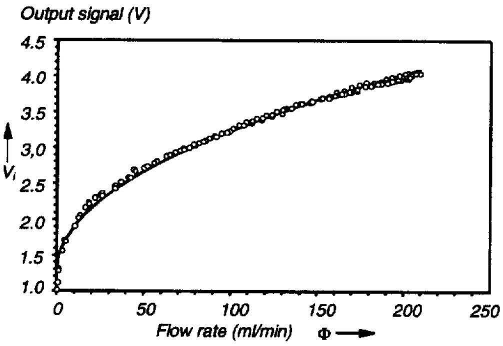

Figure 21 Typical sensor characteristic of hot-wire type in the operational mode of constant heater temperature [57]

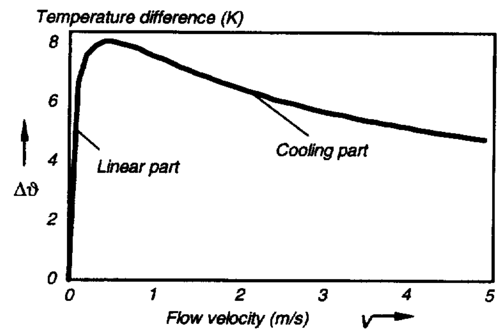

Figure 22 Typical sensor characteristic of calorimetric type in the operational mode of constant heater temperature [57]

calorimetric type is also suitable for measuring a large flow range using the so-called 'cooling part' of the sensor characteristic [30, 35, 36]. The time-of-flight type is not useful for small velocity range and requires a relatively high heat pulse for a detectable signal downstream. In general, because of their small size, micromachined gas flow sensors show an improvement of the response time comparing to conventional sensors.

With an integrated channel, micromachined flow sensors are able to measure very small mass flow rates. This attribute makes it possible for a complete micro mass flow controller to be built using a micromachined flow sensor together with an integrated

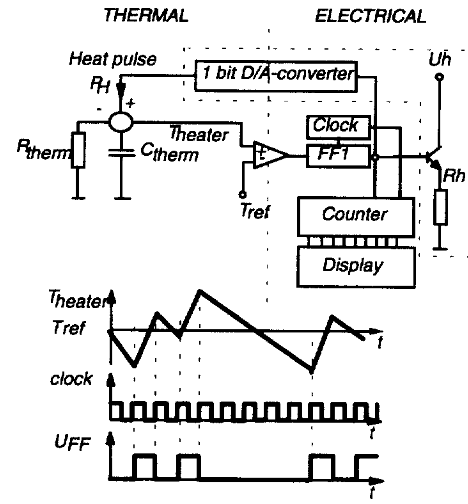

Figure 23 The principle of the thermal sigma-delta-converter

micro valve [58] or an integrated micro pump [59]. Table 4 shows the performance of micromachined flow sensors for small liquid mass flow measurements.

Micromachined thermal flow sensors have numerous applications. However, only a few micromachined thermal flow sensors are commercially available. The fact is that some important problems have not yet been solved. The unsolved problem is long-term and drift-free operation. A further problem of thermal flow sensors is the changes in the chemical properties of the fluid under measurement. The non-thermal sensors provide a solution. The liquid dosing system using an integrated micropump and a cantilever flow sensor is reported in Ref. [60]. The sensor has a flow range of 0–1 ml/min. The dosing system can regulate flow rates in the range 10–100 μl/min.

5. Development trend and outlook

The development of complex microfluidic systems consisting of different microfluidic components requires integrated flow sensors which are able to measure very small flow rates. The micro-dosing system is an interesting product for medicine, micro chemistry and micro biology.

Table 4 Performance of micromachined flow sensors with integrated microchannel for small liquid mass flow measurement

Type	Transducing principle	• Channel size (W × H) • Heater size (L × W × H)	• Measurement range • Zero-flow dissipation • Over-temperature of heater	Response time	Ref.
Hot-wire and hot-film	Thermoresistive (hot-film)	• 540 μm × 140 μm • 540 μm × 140 μm	• no data • 0.2 mW/K • 25 K	0.5–5 ms	[7]
	Thermoresistive (hot-film)	• 1000 μm × 500 μm • 300 μm × 1000 μm	0–200 ml/min water flow • 10 mW/K	3 ms	[27]
Calorimetric	Thermoresistive	• 1000 μm × 500 μm • no data	• 0... 6 μl/min water flow • no data • no data	no data	[25]

The reduction of manufacturing costs is an important aspect for the industrial use of micromachined flow sensors. Monolithic integration of electronics on the sensor chip makes this possible.

The use of an integrated analog–digital-converter on the sensor chip would ease the integration of micromachined flow sensors in an intelligence system concept [53]. The integral effect of thermal elements makes the realisation of thermal analog–digital-converters possible. Figure 23 illustrates the principle of so-called thermal sigma-delta-converters. The control of the heater is synchronised by a flip-flop. A digital output signal can be created which has a proportionate frequency concerning the heat power. The Delft University of Technology (Netherlands) is a pioneer on this subject [54, 55].

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